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An improved Q-machine source with a rotating cathode system

T. Kaneko,^{a)} H. Ishida, R. Hatakeyama, and N. Sato
Graduate School of Engineering, Tohoku University, Sendai 980-8579, Japan

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A Q machine with a rotating cathode structure and a limiter-type heat shield is described, which achieves an azimuthally symmetric and radially uniform profile of plasma density and potential. The point of emphasis is that a long time operation is realized by utilizing the latest technique of vacuum- and water-tight feedthroughs, yielding a plasma source for basic experiments with higher accuracy. © 2001 American Institute of Physics. [DOI: 10.1063/1.1405785]

I. INTRODUCTION

Since a Q-machine was constructed in 1960,¹ many fundamental experiments on plasma physics have been performed using.^{2,3} In the Q-machine the plasma is produced by a combination of surface ionization of an alkali or alkali-earth metal vapor on a hot metal plate (HP) whose work function is equal to or greater than the ionization potential of the metallic vapor and thermionic emission of electrons on HP operated at a high temperature. The plasma is confined by a magnetic field of the order of kG aligned along the axis of the device. However, it has been suggested that certain types of anomalous plasma losses may be caused by temperature gradients on HP.⁴ To put it more precisely, the plasma potential on each magnetic-field line is determined by the sheath drop in front of HP, which depends on the thermionically emitted electron flux. Since the thermionic emission exponentially varies with the HP temperature, the small temperature gradients on HP may cause a large potential gradient in the plasma. The resulting electric field may cause ion and electron drifts. Particularly the azimuthal temperature gradients are harmful because they lead to the radial particle drift and the loss of plasma via steady state convection.^{5,6}

However, if the convection is a major source of the plasma loss in these experiments, it is considered to be possible to reduce the loss rate by designing the structure of HP in which the isotherms are circular and concentric with the plate center. Jassby and Motley⁷ and Chen⁸ suggest a new HP structure in order to reduce the temperature gradients on HP. However, these are not practical because troublesome adjustments of the filament cathode structure are needed in the operation. On the other hand, Guilino *et al.*⁹ and Ooba *et al.*¹⁰ discuss and test a rotating cathode system to reduce the temperature gradients by averaging them over time. Although the filament-cathode adjustment is unnecessary in this rotating cathode system, the operational time is short because of air and water leaks at feedthroughs. In this article, we describe an improved hot plate system which is guaranteed against long time operation and achieves a symmetry and uniform plasma profile.

II. DESIGN CONSIDERATIONS

The improvement of the azimuthal temperature gradients falls into two categories. The first is a method for heating HP and the second is a structure of HP including a cathode located behind it.

A. Method for heating

There are at least three methods for heating HP. The first is to utilize radiant heat from a cathode located behind HP but it is not easy to achieve high temperature because heating efficiency is not good due to heat loss. The second is to heat HP by directly passing current through HP. In this case, however, the large current is required to keep the HP temperature high, which would distort the magnetic field near HP and would excite oscillations in the plasma because of a ripple in a power supply. The third is to heat HP by electron bombardment from a filament cathode. Since this method has good heating efficiency and easiness of controlling temperature, almost all the Q machines adopt this method. Judging from the above, we choose the electron bombardment as the method for heating HP.

B. Structure of HP

In order to improve the azimuthal temperature gradients, Jassby and Motley⁷ suggest a thick HP which has a hollow volume in its interior. Since most of the heat supplied to the rear side of HP must flow around the hollow, the heat distribution is uniformed by thermal diffusion during passing through the thick HP. Although there is a drop in temperature at the center of HP against the edge, the azimuthal temperature symmetry is expected to be realized. On the other hand, Chen⁸ suggests a coaxial cathode design, whose advantages are the achievable temperature uniformity of high degree and the easiness and accuracy of assembly due to the coaxial, modular construction. In these systems, however, the azimuthal symmetry is not provided unless the filament cathode structure for bombardment is perfectly aligned, and is considerably more difficult. Much smaller temperature gradients have been achieved by a rotating cathode system.⁹ Basically, the temperature distribution on HP is determined by the pattern of heat production on the rear side of HP. In order to achieve a symmetrical temperature distribution, the heat production must be azimuthally symmetrical. A principle of the

^{a)}Electronic mail: kaneko@ecei.tohoku.ac.jp

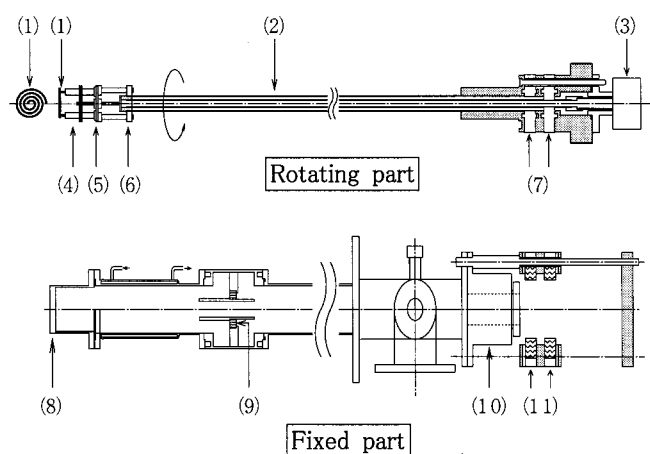


FIG. 1. Diagram of the cross section of the hot plate assembly with the rotating cathode system.

rotating cathode system is that the inevitable spatial inhomogeneities of heating power from the discrete filament cathode behind HP are converted into temporal fluctuations by rotating the whole cathode structure with sufficient frequency. In this way, the azimuthal asymmetry of heating power is averaged over one cycle and then, the thermal inertia of the HP material serves to dump the fluctuation on the average.

From what has been said above, we adopt the rotating cathode system in this experiment because we can use the conventional method for heating HP by the electron bombardment and need not to strictly align the filament cathode structure. The detailed description of the rotating cathode system is given in Sec. III.

III. DESCRIPTION

Figure 1 shows a diagram of the hot plate assembly with the rotating cathode system. This system consists of a rotating and fixed part, which include the 5.2-cm-diameter spiral-type filament cathode (1) and the 6.0-cm-diameter tungsten HP (8), respectively. The total length of the rotating part is about 150 cm. Actually, the rotating part is slipped into the fixed part. In designing this rotating cathode system, we use new techniques to satisfy the following requirements.

First, we must transfer heating power of ≈ 3 kW and cooling water as well as the torque of a motor to the rotating cathode from outside the vacuum vessel. As a rotary feedthrough for the current and water transfer, we use a double coaxial shaft (2), the diameter of which is large enough to transfer current and water. The “rotary joint” (3) is used in order to feed water into the rotating shaft. A feature of this rotary joint is to use carbon and ceramic seal rings, and thus it is proof against a long term operation under the condition of high speed rotation ≈ 3000 rpm. On the other hand, current is fed into the rotating shaft by a slip-ring collector (7) and a brush (11). The brush is mounted in the fixed part, making contact with the rotating slip-ring collector soldered to the extremity of the shaft. The brush is parts of a dynamo for car use because of its large current capacity and abrasion resistance.

It is needed to place the slip ring outside of the vacuum chamber because impurities are emitted due to abrasion between the slip ring and the brush. If the slip ring is placed outside of the vacuum chamber, part of the shaft must also be drawn to the outside of the vacuum chamber. On the other hand, it has been reported that a conventional rubber ring is not available for a vacuum seal in the case of such a large diameter shaft because of considerable difficulties with the vacuum tightness under the condition of the larger relative velocity between the shaft and rubber ring.⁹ Thus, a new method, “ferrofluidic seal” (10), is adopted in this system as the vacuum seal instead of the rubber-ring seal. This ferrofluidic seal effectively utilizes the reaction of ferrofluid to magnetic field, maintaining vacuum by forming the fluid seal ring. Because this fluid seal ring is not abraded differently from the rubber seal ring, it works for a long term ≈ 10 years under the conditions of high vacuum $\approx 1 \times 10^{-9}$ Torr and high speed rotation ≈ 3000 rpm.

Second, the filament support must be proof against melt-down from heat. Since the distance between filament and HP is about 5 mm and the cooling water cannot be fed to the support due to the structure restriction, the temperature around the filament attains more than 2000°C . For this reason the filament is supported by two 8-mm-diameter molybdenum rods (4) whose melting point is 2620°C . These rods are relayed by a molybdenum plate (5) and is held to a copper socket (6) installed to the extremity of the shaft (2).

Third, it is required to be equipped for easily centering the filament cathode on the axis of HP. In order to make the cathode centered, the shaft which supports the filament cathode is guided by a bearing (9). The bearing is required to stably operate in a vacuum, in a strong magnetic field, at a high voltage difference between the shaft and ground, and furthermore at a high temperature because the bearing is near HP. Therefore, it is expected to have the properties of cleanliness, nonmagnetization, electric insulation, and heat resistance. Consequently, the bearing made of nonmetallic material, namely, ceramic is adopted, which can be used under the condition of pressure $P \approx 10^{-7}$ Torr, temperature $T \approx 800^\circ\text{C}$ and voltage $V \approx 3$ kV.

IV. MEASUREMENTS

The experiment is carried out under following conditions, the magnetic field $B = 2$ kG, the plasma density $n_p \approx 1 \times 10^9 \text{ cm}^{-3}$, the electron temperature $T_e \approx 0.2$ eV, the ion temperature $T_i \approx T_e$, and the ion flow energy $E_i \approx 10T_e/e$. A background gas pressure is 4×10^{-7} Torr. The plasma is collisionless in the sense that collision mean free paths of electrons and ions are longer than the plasma length (≈ 310 cm). The heating current I_H for the filament cathode, the bombardment voltage V_B and the current I_B are provided by 30–100 and 2000 V–4 A power supplies, respectively. To obtain the plasma density stated above, $I_H = 50$ –60 A, $V_B = 1.2$ kV, and $I_B = 2.2$ A are required (the hot plate bombardment power $P_B: 2.64$ kW). When the filament cathode is rotated, no air and water leaks are detected in more than twelve straight hours of operation for six months. A small movable Langmuir probe located 60 cm from HP is used to measure

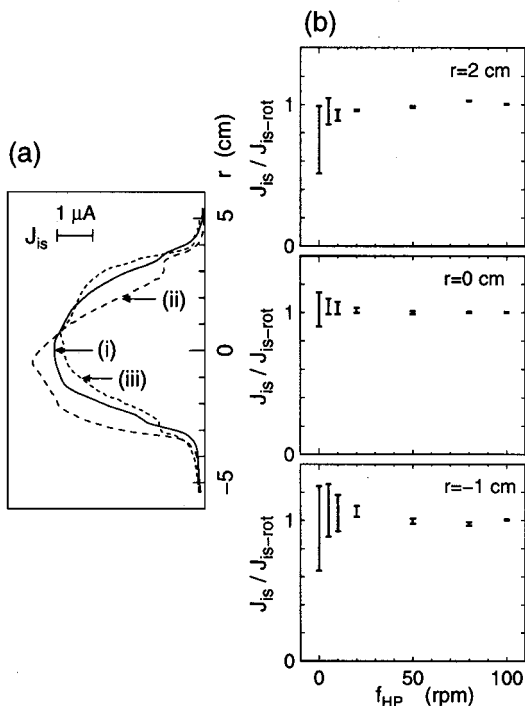


FIG. 2. (a) Radial J_{is} (ion saturation current of the probe) profiles at $f_{HP} = 200$ rpm (i) and $f_{HP} = 0$ rpm (ii) and (iii), respectively. (b) Deviations of J_{is} at each radial position as a function of f_{HP} (rotating frequency).

plasma parameters and their two-dimensional profiles across the plasma. Here, we mainly measure ion saturation current J_{is} profiles of the biased probe in order to estimate the temperature distribution on HP surface because J_{is} which is proportional to plasma density is determined by the temperature of HP.

At first, radial profiles of J_{is} are shown in Fig. 2, together with deviations of the ion saturation current as a function of rotation frequency f_{HP} . Here, the deviations at each f_{HP} are obtained from the temporal variation of J_{is} , which is normalized by the temporally constant ion-saturation current J_{is-rot} at enough high f_{HP} . In Fig. 2(a), solid line (i) and dotted lines (ii) and (iii) indicate the radial J_{is} profiles at $f_{HP} = 200$ rpm and $f_{HP} = 0$ rpm, respectively. At $f_{HP} = 0$ rpm, the J_{is} profile is localized on the left-hand side (ii) or right-hand side (iii) depending on the setting situation, i.e., filament location. On the other hand, the J_{is} profile at $f_{HP} = 200$ rpm (i) becomes symmetrical due to the averaging effect. The averaging rate is a function of both f_{HP} and heat conductivity of HP. Since the heat conductivity cannot be varied, we vary f_{HP} for the purpose of finding the optimum value of f_{HP} . Figure 2(b) demonstrates that the deviations of J_{is} at each radial position decrease with an increase in f_{HP} and are almost zero at $f_{HP} = 100$ rpm. Thus, the sufficient rotation frequency to average the HP temperature gradient is found to be $f_{HP} = 100$ rpm. In the following experiment, however, we adopt $f_{HP} = 200$ rpm for the optimum value in order to obtain the perfectly averaged J_{is} profile.

Figure 3(a) shows bird's-eye and contour views of J_{is} at $f_{HP} = 0$ rpm and $\theta = 0^\circ$. Here, θ is the rotational angle of the

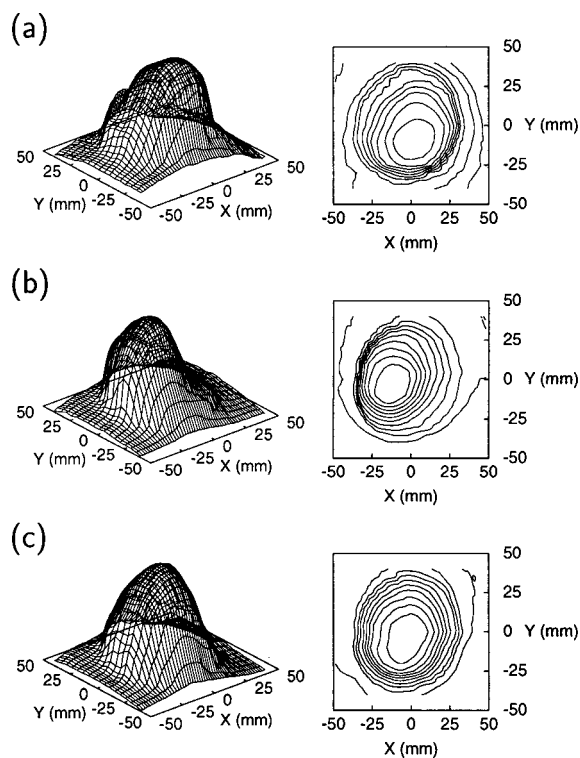


FIG. 3. Bird's-eye and contour views of J_{is} at (a) $f_{HP} = 0$ rpm, $\theta = 0^\circ$; (b) $f_{HP} = 0$ rpm, $\theta = 180^\circ$; (c) $f_{HP} = 200$ rpm.

filament cathode, indicating the filament location. It is found that J_{is} , or the plasma density is localized on the lower right-hand side of HP. This high density region corresponds to the region where the density of the filament is slightly high owing to the discrete filament. When the filament cathode rotates by 180° [Fig. 3(b)], the high density region moves to the above left-hand side, namely, rotates by 180° . These results indicate that the dense region of the filament gives rise to an increase in bombardment current and yields a high temperature region on the HP surface, resulting in a local increase in the plasma density. In the case of $f_{HP} = 200$ rpm, however, the high or low density region are averaged out in the azimuthal direction and the contour view of J_{is} presents almost concentric circles, as shown in Fig. 3(c). As a result, the azimuthal symmetry of the plasma density is achieved by the rotating cathode.

In this case, however, the plasma density decreases in the edge region of HP, i.e., the considerable radial density gradient exists on the plasma cross section even inside the HP diameter. Although this radial density gradient may not directly cause a radial ion drift, there is possibility to give rise to some kinds of instabilities.

V. MODIFICATIONS

Now that the rotating cathode system is confirmed to achieve the azimuthal symmetry of the plasma density, the next step is to flatten the plasma density profile in the radial direction. Since the origin of the radial inhomogeneity is a drop in temperature at the HP edge, we install a heat shield which plays an important role in reducing the heat radiation from the side of HP. Side views of two types of the heat

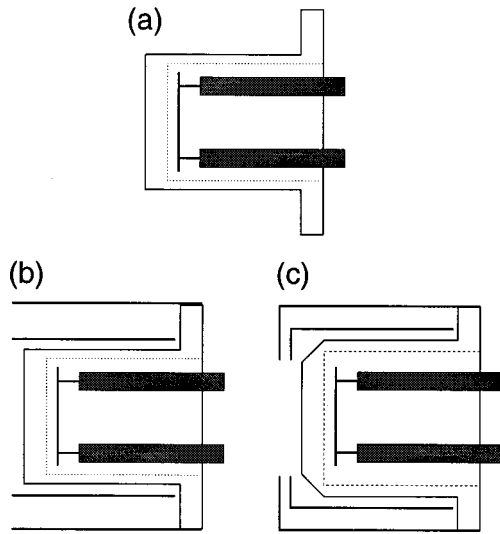


FIG. 4. Side views of the hot plate with (a) no heat shield; (b) the cylinder-type heat shield; (c) the limiter-type heat shield.

shield are shown in Fig. 4, together with the side view of only HP with no heat shield [Fig. 4(a)]. Figure 4(b) shows a cylinder-type heat shield which has double coaxial cylinders and covers the extremity of HP. Since the distance between HP and the inner cylinder is about 5 mm, the temperature of the inner cylinder is estimated to be about 2500 °C. Thus, the inner cylinder is made of tantalum whose melting point is 2996 °C. On the other hand, the outer cylinder is made of molybdenum because its temperature is reduced by the inner cylinder. We usually use this type of heat shield but this heat shield cannot completely prevent the temperature at the HP edge from dropping because the diameter of the filament is smaller than that of HP. Therefore, electrons emitted from the filament cannot bombard the edge of HP. Figure 4(c) shows a limiter-type heat shield which has brims to shade the edge of HP surface. The inner heat shield is made of tungsten whose melting point is 3389 °C because its temperature is considered to become higher than that of the cylinder-type heat shield. The material of the outer heat shield is the same as that of the cylinder-type. Added to this, a new HP is prepared, the side shape of which is trapezoid. The body diameter of the new HP is 7 cm, which is larger than that of the conventional HP (6 cm). The surface diameter of the new HP is 5 cm, which is equal to an aperture diameter of the limiter. Owing to this structure, the practical diameter of the HP surface which produces the plasma is considered to be nearly equal to the filament diameter. Therefore all the region of the HP surface is expected to be bombarded by emitted electrons and to be uniformly heated not only in the azimuthal direction but also in the radial direction.

Figure 5 shows bird's-eye and contour views of J_{is} at $f_{HP}=200$ rpm with or without the heat shield. Even if the heat shield is not installed [Fig. 5(a)], the azimuthal symmetry is achieved because the filament cathode is rotating. However, the plasma diameter is small and the plasma density at the HP edge is much less than that in the HP center, resulting in the existence of the radial density gradient. As

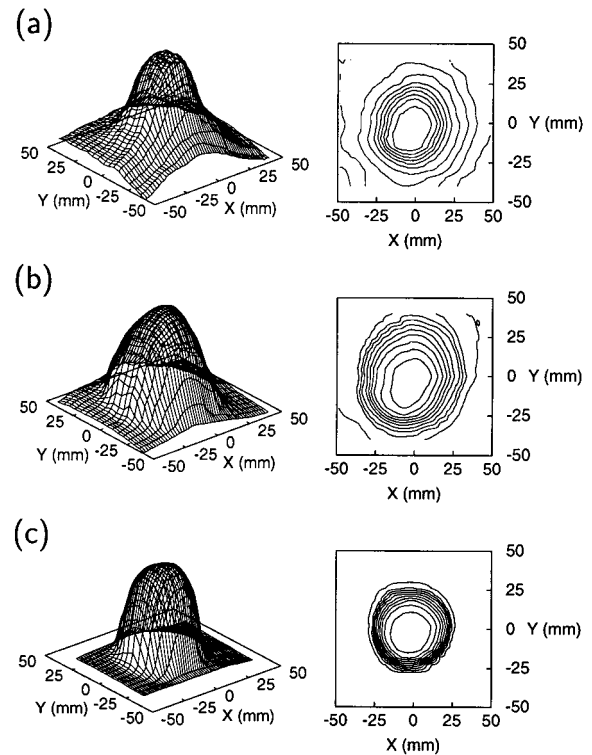


FIG. 5. Bird's-eye and contour views of J_{is} at $f_{HP}=200$ rpm with (a) no heat shield; (b) the cylinder-type heat shield; (c) the limiter-type heat shield.

mentioned above, this is caused by the heat radiation from the side of HP. When the cylinder-type heat shield is installed [Fig. 5(b)], on the other hand, the plasma diameter becomes larger than that in the absence of the heat shield. This result indicates that the heat radiation is reduced by the shield and the HP edge temperature is kept at a reasonable value. However, the radial gradient of the plasma density still remains due to the difference between the filament and HP diameters. Figure 5(c) gives a two-dimensional J_{is} profile in the case where the limiter-type heat shield is installed. The plasma density profile projected on the effective HP surface is almost flat and the boundary of the plasma column is sharp. The reason why the diameter of the plasma is smaller than that in the case of the cylinder-type heat shield is that the brim of heat shield limits the plasma. Finally, we can obtain the ideal profile of the plasma density by using the limiter-type heat shield as well as the rotating cathode system.

Figure 6 shows the plasma potential profile at $f_{HP}=200$ rpm with the limiter-type heat shield. The potential

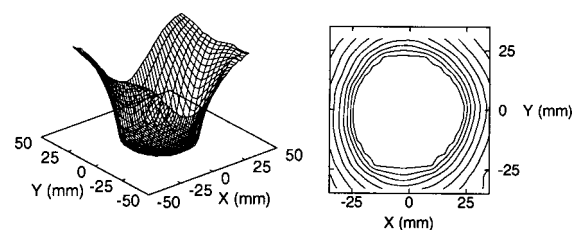


FIG. 6. Bird's-eye and contour views of ϕ (plasma potential) at $f_{HP}=200$ rpm with the limiter-type heat shield.

profile is radially uniform in the core region, symmetrical in the azimuthal direction, and ideally well shaped.

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